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REVIEW ARTICLE

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A literature review of smart warehouse operations management

Abstract E-commerce, new retail, and other changes have highlighted the requirement of high efficiency and accuracy in the logistics service. As an important section in logistics and supply chain management, warehouses need to respond positively to the increasing requirement. The "smart warehouse" system, which is equipped with emerging warehousing technologies, is increasingly attracting the attention of industry and technology giants as an efficient solution for the future of warehouse development. This study provides a holistic view of operations management problems within the context of smart warehouses. We provide a framework to review smart warehouse operations management based on the characteristics of smart warehouses, including the perspectives of information interconnection, equipment automation, process integration, and environmental sustainability. A comprehensive review of relevant literature is then carried out based on the framework with four perspectives. This study could provide future research directions on smart warehouses for academia and industry practitioners.

Keywords smart warehouse, operations management, interconnection, automation, integration, sustainability

1 Introduction

In recent decades, the rapid developments in technology have led to disruptive growth in the logistics section. Smart warehouses have emerged as a product of smart technologies, fueling a wave of an industry transformation that could drive dramatic changes. Going by the boom of e-commerce, e-commerce warehouses are among the most promising applications among various smart warehouses. According to State Post Bureau of PRC (2020), the volume of express delivery in the "Double 11" online shopping festival has reached over 3.9 billion packages, and the total volume of express delivery in 2020 exceeds 70 billion packages. Retail and technology giants are investing heavily in smart warehouses to process the explosive e-commerce logistics demand in a timely and cost-effective way. For instance, Alibaba's Cainiao invests in smart logistics parks in China with a "smart" system to manage warehouse complexity (Cainiao, 2018). Amazon launched a fulfillment center with a robotic mobile fulfillment system (RMFS) in Sparrows Point in late 2018, which features Amazon's robotic technology and innovative processes that enable the associates to exceed customer expectations (Technical.ly, 2019) (see Fig. 1). The concept of smart warehouses is not limited to the e-commerce industry. Other industries also tap into logistic potentials through smart warehouses to deal with the explosion of logistic needs. As a part of the smart grid plan in China, State Grid Corporation of China has deployed smart warehouses in all its provincial branches, which are used to store emergency materials and daily spare parts of

Fig. 1 RMFS with mixed shelves and picking station (accessed via amazonrobotics.com).

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the grid system (see Fig. 2). Smart warehouses help State Grid improve the capability of emergency response and daily material management. Furthermore, in the port industry, automated container terminals (ACTs) also belong to a type of "smart warehouse" system. Shanghai Yangshan ACT is the largest ACT globally, with 130 automated guided vehicles (AGVs) (China Daily, 2017). Based on the examples above, smart warehouses have spread across many industries and become common choices to cope with the market's changing needs and enhance productivity.

Fig. 2 Smart warehouse of State Grid Jiangsu Electric Power Co., Ltd. (accessed via tech.jschina.com.cn/jrsd/201812/t20181219_2118902.shtml).

Driven by industry needs, academic research on smart warehouses has been a hot topic. Some scholars have put forward their idea on smart warehouses and smart logistics. According to the summary of McFarlane et al. (2016), the term "intelligent logistics" refers to different logistics operations, which are planned, managed, or controlled in a more intelligent way compared with conventional solutions. Wen et al. (2018)'s work shows a strong requirement for automation and intelligence technology in smart logistics. In our opinion, smart warehouses are the collection of smart technologies in warehouse section and a series of operations management practices to make warehouses operate in a "smarter" way. Smart warehouses have developed into an integral of cutting-edge technologies, warehouse processes, and warehouse operations management. The basic characteristics of smart warehouses can be classified into the following perspectives:

- **Information interconnection.** Information interconnection involves the top-level design of smart warehouses. It is the base of smart warehouses and operational management. Based on technology derived from the Internet of Things (IoT), cyber–physical systems (CPS), and other emerging technology, information flow can be shared and processed by numerous logistics nodes and thus produce extra values.
- **Equipment automation.** Equipment automation describes the characteristics of smart warehouse at strategic and tactical levels. Automation is the technical support of the smart warehouse. Equipped with automatic facilities, smart warehouses can achieve high automation levels in warehouse activities. Equipment automation can improve warehouse productivity while reducing the need for manual labor. Besides, the operations management of smart warehouses pays more attention to equipment characteristics on strategic-level decisions and product characteristics on tactical-level decisions, providing a holistic view of the technology, and improves the precision of decision-making.
- **Process integration.** Process integration is the requirement of smart warehouse operations management and functions as operational support in the framework. Process integration tries to implement overall planning among various warehouse processes and focuses on the new operational problems arising in the operation of smart warehouses. The objective of process integration is to achieve coordination while eliminating discordance of warehouse operations management.
- **Environmental sustainability.** Environmental sustainability is the future of smart warehouses, supported by equipment automation and process integration. The sustainable development of smart warehouses concerns the problems relevant to the environment, such as energy consumption and carbon emission. The operations management of smart warehouses on strategic, tactical, and operational levels should implement in an eco-friendly way to create a sustainable roadmap in the warehouse section.

To characterize smart warehouses' basic characteristics and perspectives, we build a conceptual framework, which is shown in Fig. 3. In this framework, smart warehouses are building roofs in the environment of warehouse operations management. Information interconnection is the base of warehouses, which provides information exchange channel and basic technological support for the warehouse system. Equipment automation and process integration are the two pillars of the warehouse. Equipment

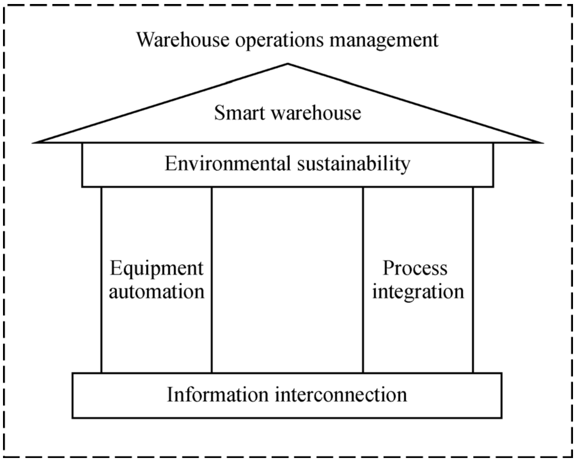

Fig. 3 The conceptual framework of a smart warehouse.

automation aims to achieve automatic operation through the design and deployment of automation equipment, and the implementation of proper strategies. It provides support at strategic and tactical levels. Process integration aims to control and coordinate various warehouse processes and technologies. It provides support at the operational level. Environmental sustainability is the beam of warehouses, which is supported by interconnection, automation, and integration. These four perspectives, namely, information interconnection, equipment automation, process integration, and environmental sustainability, build the conceptual framework of smart warehouses. Warehouse operations management is the theme running through the four perspectives.

The remainder of this review is organized as follows. Insights from previous literature reviews and detailed research methodology are proposed in Section 2. Section 3 presents the interconnection aspect by applying IoT and CPS in warehouse design and control. Section 4 reviews articles related to strategic and tactical decisions and provides an overview of smart warehouses' automation technology. Section 5 proposes the process integration of smart warehouses and classifies articles according to different operational problems. Section 6 extracts the environmental sustainability issue from warehouse operations management to propose a green warehouse roadmap. The last Section summarizes the current research status and proposes some open research questions for future research.

2 Research methodology

2.1 Insights from previous literature reviews

In the last two decades, several literature reviews have discussed some related topics of warehouse operations management, which may provide some insights to our research. To justify the research scope of "smart warehouse operations management" and derive the need for the content analysis, we summarize previous reviews that may relate to our research. The related literature reviews are then classified into two groups: Literature reviews before and after 2015, respectively. Table 1 summarizes these literature reviews.

2.1.1 Literature reviews before 2015

Given that smart warehouses have emerged in recent years, the earlier published reviews discussed less about current warehouse development and smart technologies. But the earlier reviews can still bring insights into the basic concepts related to warehouse operations management. In Rouwenhorst et al. (2000)'s review, warehouse design problems and models are presented at strategic, tactical, and operational levels. Gu et al. (2007) present a review of warehouse operation planning based on the classification according to the basic warehouse functions, including receiving, storage, order picking, and shipping. Gu et al. (2010) provide some comments on warehouse design

Table 1 Summary of previous literature reviews

Review article	Topic	System/Concept
Rouwenhorst et al. (2000)	Warehouse design and control	Manual warehouse
Gu et al. (2007)	Warehouse operation	Manual warehouse
Gu et al. (2010)	Warehouse design and evaluation	Manual warehouse
de Koster et al. (2007)	Warehouse design and control about order picking	Manual warehouse
Roodbergen and Vis (2009)	AS/RS design and operation	AS/RS
Gagliardi et al. (2012)	AS/RS performance evaluation	AS/RS
Ben-Daya et al. (2017)	IoT and supply chain management	IoT-enabled supply chain
Manavalan and Jayakrishna (2019)	IoT in sustainable supply chain management	IoT-enabled supply chain
Winkelhaus and Grosse (2020)	Logistics 4.0, IoT, CPS	Logistics 4.0
Boysen and Stephan (2016)	AS/RS single crane scheduling	AS/RS
Jaghbeer et al. (2020)	Automated order picking systems and their design and evaluation	Automated warehouse
Custodio and Machado (2019)	Flexible automation in warehouses	Automated warehouse
Fottner et al. (2021)	Research framework of autonomous intralogistics systems	Autonomous intralogistics systems
Glock et al. (2021)	Assistive devices for manual materials handling	Assistive devices
Boysen et al. (2019)	Design and operation of e-commerce warehouse	E-commerce warehouse
Azadeh et al. (2019a)	System analysis, design, and operation of robotized and automated warehouse systems	Robotic warehouse
Fragapane et al. (2021)	Application, planning, and control of AMR	AMR
Bartolini et al. (2019)	Green warehousing	Green warehouse
This paper	Smart warehouse operations management	Smart warehouse

based on the following warehouse design problems: Overall structure, sizing and dimensioning, equipment selection, operation strategy selection, and department layout. de Koster et al. (2007) stress the importance of the order picking process. Optimization problems related to layout design, storage assignment, routing, order batching, and zoning are reviewed.

Automated Storage and Retrieval System (AS/RS) has attracted much attention from earlier reviews. Roodbergen and Vis (2009) provide an overview of the AS/RS literature for a range of issues, including physical design, storage assignment, batching, dwell-point location sequencing, and performance evaluation. Various models for AS/RS performance evaluation are surveyed in Gagliardi et al. (2012)'s work. Analytical models and simulations are the two types of models commonly used in research.

2.1.2 Literature reviews after 2015

Recent reviews focus more on the emerging warehouse technologies and new developing trends. IoT, Industry 4.0, and other emerging technologies influence the way of information exchange in warehouses. Ben-Daya et al. (2017) reveal the role of the IoT and its impact on supply chain management. Radio frequency identification (RFID) tags are the major IoT technology studied in previous warehousing research. Manavalan and Jayakrishna (2019) review IoT's role in achieving sustainable goals in supply chain management. The importance of digitalization and the influence of IoT in the overall supply chain management are analyzed. The criteria for achieving business readiness for Industry 4.0 transformation are concluded. Winkelhaus and Grosse (2020) propose a systematic literature review for Logistics 4.0. The application of IoT, CPS, and other technologies related to Logistics 4.0 are summarized in the review.

The rapid development of automation technology has dramatically improved the automation level of warehouse systems. In this development process, different concepts related to automated warehouses have emerged. Boysen and Stephan (2016) classify single crane scheduling problems in AS/RS in three perspectives: Layout, order characteristics, and objectives, and then survey crane scheduling problems. Jaghbeer et al. (2020) present an analysis of the literature related to automated picking systems and identify and study the link between design and performance. Custodio and Machado (2019) discuss flexible automation in warehouses and construct a framework for designing flexible automated warehouses. Fottner et al. (2021) investigate the definition and research framework of autonomous intralogistics systems, which enable self-contained, decentralized planning, execution, control, and optimization of internal material and information flows through cooperation and interaction with other systems and with humans. A typical autonomous warehouse system is a segment of autonomous intralogistics systems. Glock et al. (2021) provide a review of technical assistive devices for manual materials handling. Papers that discuss assistive devices on the warehousing system are identified in their systematic literature review.

New warehouse concepts and applications have been derived in recent years. These concepts may be similar to smart warehouses we characterize. Boysen et al. (2019) survey relevant literature about warehouse systems for e-commerce warehouses. Warehouse systems need to cope with the requirements of e-commerce, including small orders, large assortment, tight delivery schedules, and varying workloads. The warehouse systems adopted in e-commerce warehouses are investigated in their review. Azadeh et al. (2019a) review the developments of robotized and automated warehouse systems. Research on different warehousing systems is categorized into three categories: System analysis, design optimization, and operational planning and control. The systems identified in this review are essential for warehouse automation. The integrated models and systems are mentioned as the direction of future research for established systems. Fragapane et al. (2021) review the application of autonomous mobile robots (AMRs) in intralogistics and the corresponding planning and control problem. AMRs are industrial robots that evolve from AGVs and have been widely used in warehousing and other intralogistics operations. For the sustainability topic in warehouses, Bartolini et al. (2019) provide an exhausted macroscopic review about green warehousing. Existing literature about green warehousing is categorized into three macro-themes: Green warehouse management, the environmental impact of warehouse building, and energy saving in warehousing.

To some extent, the concept of smart warehouses proposed in our review may overlap technical perspectives with the abovementioned reviews. Most of the existing reviews define and classify their research scope from the technical aspect. In other words, previous studies usually focus on a specific type of warehouse equipment or technology. In our opinion, smart warehouse is not limited to warehouse concepts like e-commerce warehouse and green warehouse. Smart warehouses should be a broader concept that concerns leading warehouse technology and applications and intrinsic principles of warehouse operations management. This broad meaning offers a wide space for the research of smart warehouse operations management, which could be the most promising trend in warehouse management. We develop a novel review framework based on the basic characteristics proposed above. Instead of classifying literature by technical aspect, the classification and analysis of literature in our review are based on the characteristics of smart warehouses. This classification framework provides a solution that covers both technical and operational aspects of smart warehouse operations management. This review's main innovation and contribution is that we provide a comprehensive literature review for smart warehouse operations management based on a novel review framework that reveals the existing inner links of smart warehouse operation. We expect that the novel framework of our review could provide some new insights into smart warehouse operations management.

2.2 Literature search and selection strategy

To conduct literature search and selection methodology systematically and transparently, we follow the guidelines presented by Durach et al. (2017). The sample is generated through the following steps:

Step 1: Define the research scope.

According to the topic, research on integration decision and optimization of smart warehouses is reviewed in this research. Based on the previous research, the research scope could be refined as suggested in Section 1.

Step 2: Determine the required characteristics for primary studies.

Based on Step 1, the inclusion and exclusion criteria should be established to determine if an article is relevant to the review:

(1) Research related to smart warehouse operations management can be included.

(2) Research related to warehouse operations management can be included. Research focusing on supply chain management, inventory management, and warehouse location should be excluded.

(3) Research topics that are not relevant to the logistics section (e.g., data warehouse and knowledge warehouse) should be excluded.

(4) Research in English with a publication date from January 2015 to December 2020 can be retained.

(5) Research published in high-impact journals that meet all following criteria can be included to ensure focus on the research topic:

a) The journals should be peer-reviewed.

b) The journals should be cited by the Science Citation Index Expanded (SCIE) or Social Sciences Citation Index (SSCI) database.

c) According to the 2019 Journal Citation Reports (JCR), the journals should rank in the first quartile in the related JCR category.

(6) The research with a document type of article or review can be included.

Step 3: Retrieve samples of potentially relevant literature.

Web of Science Core Collection is used as the database in this review. To implement these criteria defined in Step 2, we restrict the period within the years range from 2010 to 2020 and select the options SCIE and SSCI in the search setting. We use the initial keywords set gathered from the topics of previous literature reviews as the starter of the search. The papers in the initial searching results are analyzed and some keywords are extracted from the initial search result to refine the keywords list. The refined keywords set are listed in Table 2.

Step 4: Select pertinent literature.

In this step, the inclusion and exclusion criteria listed in Step 2 are applied. Relevant literature is selected and classified according to the review framework. A total of 657 publications were selected.

Step 5: Synthesize literature.

Literature is synthesized and examined in the following sections.

2.3 Result analysis

2.3.1 The trend of publications with time

To analyze the research trend of smart warehouses, we collect the data of publication distribution from the search result. Figure 4 shows an increase in the number of publications since 2010. These results indicate the growing research interest in different aspects of smart warehouses.

The general trend of the publications is on the rise. The

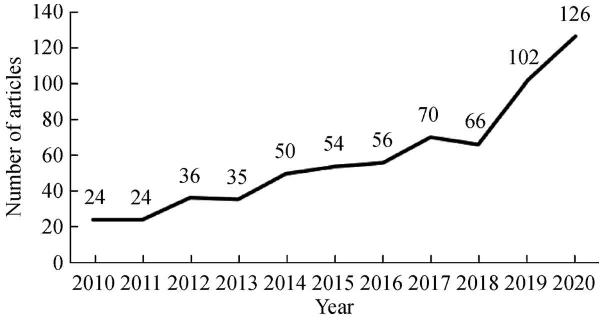

Fig. 4 Number of publications with keywords related to smart warehouse.

Table 2 Keywords set

Category	Initial keywords	Keywords added by refinement
Warehouse fundamental	Warehouse, design, operation	Intralogistics
Automated warehouse facilities	Automated, automation	AGV, robot, storage, retrieval
Information	IoT, CPS	RFID, warehouse management system (WMS)
Warehouse operation	Picking, retrieving, scheduling, batching, routing	Conflict, congestion, service
Sustainable warehouse	Sustain	Carbon, energy, green
Excluded keywords	Manual, inventory, data warehouse, knowledge warehouse	

emergence and implementation of new warehousing technologies have contributed to the increasing trend. We observe that articles published in 2015–2020 focus more on emerging equipment, such as RMFS, autonomous vehicle storage and retrieval system (AVS/RS), and shuttle-based storage and retrieval system (SBS/RS). Furthermore, a significant boost is observed in the number of articles related to warehouse operations management and optimization from 2018 to 2020. The number of articles published in 2020 is almost twice the number of articles published in 2018. The increasing trend of the number of articles shows that the concern on the operations management and optimization of warehouses has significantly increased, reflecting the rapid development and growing need for warehousing systems.

2.3.2 Keywords co-occurrence analysis

To reveal the internal relationships and classify the main topics of existing research, we conduct keywords co-occurrence analysis by VOSviewer. In the figure of keywords co-occurrence network, each keyword represents a topic or concept in warehouse research and is shown as nodes in the figure. The arcs between different keywords indicate the co-occurrence between the two topics or concepts. The node size represents the occurrence time of a keyword, and the thickness of an arc means the time of co-occurrence of two keywords. To illustrate the evolution of the research topics, we divide the selected articles into two parts: The article published in 2010–2014 and the article published in 2015–2019. The keywords co-occurrence analysis of articles in the two parts is conducted separately.

Figures 5 and 6 show the main research topics of articles published in 2010–2014 and 2015–2019, respectively. Both networks have three clusters. The green clusters show the fundamentals of warehouse research, such as the basic concept of optimization, system, and management. The core of the red clusters is the warehouse design. Some design concepts are included in the clusters, for example, travel time, performance, and some warehouse systems such as AS/RS. The blue clusters mainly include the warehouse activities and decision problems of warehouse research, such as storage and picking.

By comparing the two networks, some keyword changes are observed. First, design, storage, and picking are the main topics in warehouse research. Various studies have been undertaken on these topics. Second, the concern of new technologies is reflected in the analysis. The emergence of SBS/RS, robots, and other novel warehouse systems raises new research problems for researchers. Third, the concern on warehouse operations management has been increased in these years. This increase can be directly concluded by the emergence of the node

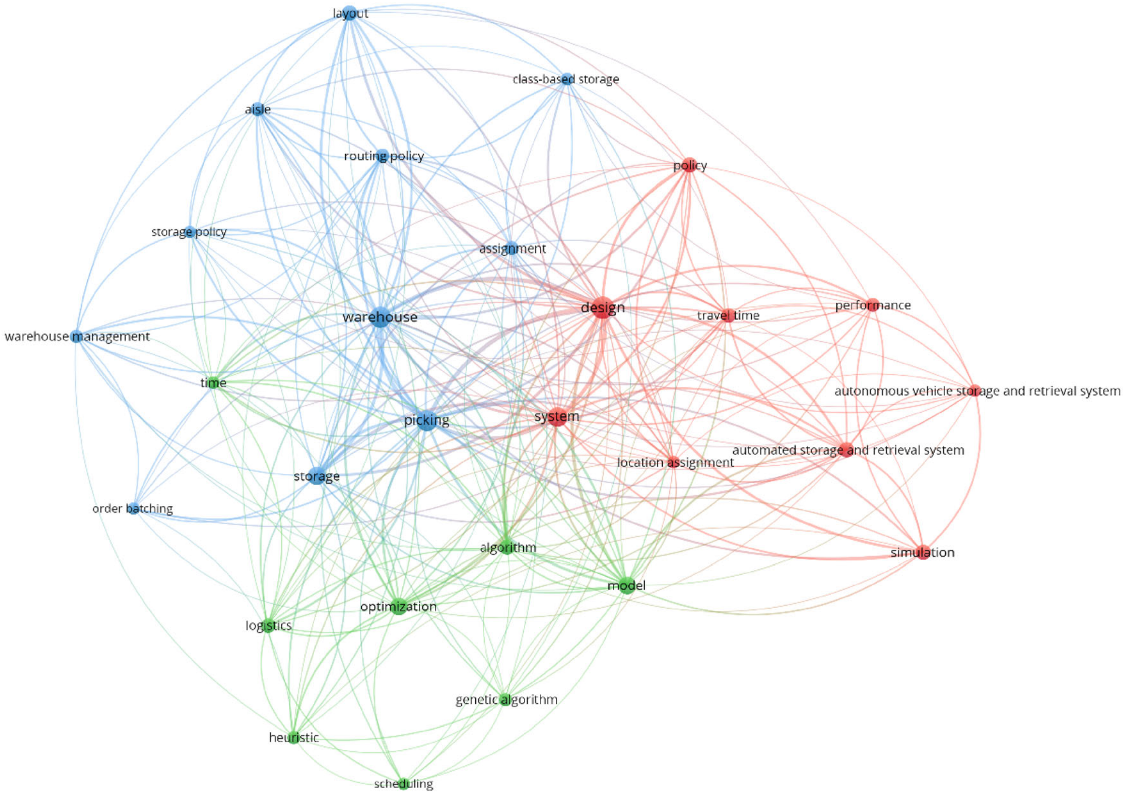

Fig. 5 Clusters of keywords co-occurrence (2010–2014).

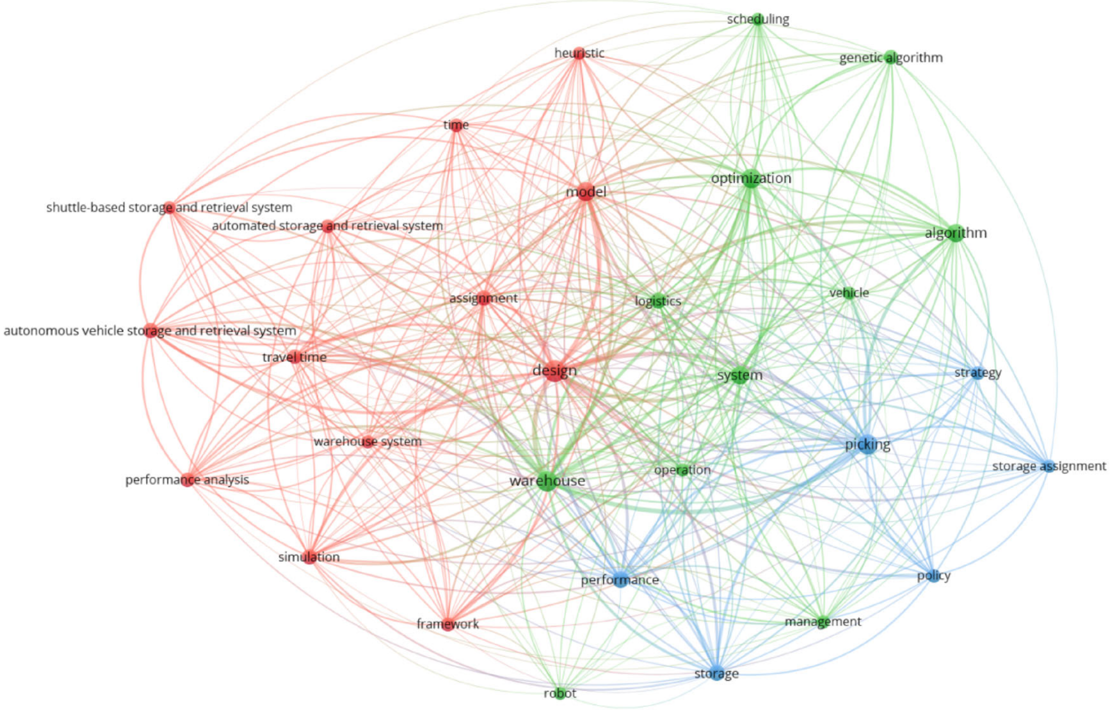

Fig. 6 Clusters of keywords co-occurrence (2015–2020).

"operation" and the node "assignment". Meanwhile, attention to some specific issues, such as layout design, aisle configuration, and class-based storage, has been weakened. The complex links among keywords indicate that the integrated research of some operations management problems becomes increasingly popular.

2.3.3 Analysis of different research methodologies

From the existing research on warehouse operations management, four main research methodologies can be concluded: Travel time models, queuing network models, mathematical programming, and simulation.

Travel time models and queuing network models are commonly used models for the evaluation of warehouse systems. Travel time refers to the time that a resource or item moves from a location to another, which is one of the most concerning indicators in warehouse systems. Travel time models can be derived based on the operating mechanisms of warehouse systems. Using travel time models, warehouse operators can easily calculate the system travel times and throughputs. Travel time models can be used as the basis of simulation and queuing networks. However, travel time models have difficulty in evaluating the interaction of different factors, such as the serial and parallel processing of different tasks and the accompanying resource occupation problem. Queuing network models are applied to characterize these complex interactions. Similarly, travel distance models could obtain the moving distances of warehouse resources and can also be used to calculate the corresponding cost and energy consumption.

Queuing network models are used for the modeling of complex systems. Warehouse systems can be modeled as multistage systems using queuing networks. The storage/retrieving tasks, which are usually referred to as the customers of the queuing theory, may queue in somewhere of the system to wait to be processed by facilities or resources of the warehouse system. Once a task is completed, it will leave the system, and the resources occupied by the task will be released to serve another task. Queuing network models provide complements to make up for the shortcomings of travel time models. Queuing network models can obtain analytical solutions by the derivation of queuing theory and showing productivity in the comparison of operational strategies in warehouse strategic, tactical, and operational decisions. However, the modeling process of travel time models and queuing network models relies on system operations assumptions. Sometimes the strong assumptions may distort the model and reduce the usability of the solutions and conclusions obtained by the models.

Mathematical programming builds linear programming, nonlinear programming, or mixed-integer linear programming models for warehouse optimization. It aims to provide the right choice and give detailed instructions for warehouse operations problems. Mathematical programming is used to obtain operational decisions, such as order processing, job scheduling, and resource assignment. For strategic and tactical decisions, mathematical programming can also be used to optimize warehouse layout design and storage assignment. By conducting sensitivity analysis, the impact of different strategic and tactical decisions on the model's objective can be tested and concluded. A mathematical model is built by clarifying first the decision problem and then the objective need. Constraints depict the internal operating principles of system operation. Mathematical programming is usually applied in the decision of deterministic problems. Some stochastic problems can also be modeled by stochastic programming.

The mathematical programming model can be solved by applying some commercial solvers. However, most warehouse operations problems are non-deterministic polynomial (NP)-hard, which means that commercial solvers cannot be used. Some metaheuristic algorithms are employed to obtain near-optimal solutions in a short time. The common metaheuristic algorithms employed in warehouse operations research include genetic algorithm, simulated annealing algorithm, particle swarm optimization algorithm, and neighborhood algorithm. Some researchers apply exact algorithms, such as branch and bound and dynamic programming, to obtain exact solutions.

Warehouse systems can also be modeled by simulation. Simulation models can depict the system reality and operation mechanism in high accuracy to adapt to various warehouse systems. Simulation models are often used to compare and demonstrate the proposed strategies, algorithms, or methods. When modeling a warehouse system by queuing networks or mathematical programming is complex, simulation can provide a possible way to obtain the solutions. However, the conceptualization and design of the simulation model may require lots of work. The solving process of the simulation model could be time-consuming. Besides, simulation models can hardly obtain optimal solutions or near-optimal solutions for some specific warehouse operations problem.

From the reviewed literature, we can find that researchers are more inclined to use travel time models and queuing network models for analysis of the strategical decision of warehouse operations management. Some algorithms are developed as parts of imposed strategies or assignment rules. To deal with the operational decision problems, mathematical programming models are more preferred. For most operational decisions, heuristic algorithms are developed to work out detailed operational plans efficiently. Simulation models can be applied to a variety of decision problems. When using travel time models or queuing network models in research, simulation models are often used to validate the derived models. Travel time models, travel distance models, and queuing network models can provide essential inputs like travel time or distance in simulation models.

2.4 Summarization of reviewed literature

To establish a comprehensive classification of the reviewed literature related to smart warehouse operations management, we summarize the reviewed literature in Table 3.

3 Information interconnection

In the last decades, CPS and IoT, which emerged as the extension of computer networks into every device and object, have become essential supporters for enabling the interconnection of logistics activities. CPS and IoT turn the ideal concept into a reality that goods, logistics facilities, and logistics elements are connected and communicated (Ben-Daya et al., 2017; Lee et al., 2018; Yang et al., 2019). In today's warehouse practice, RFID, warehouse management system (WMS), augmented reality (AR), reinforced learning, and other emerging technologies enhance the interconnection between different processes and entities (Dou et al., 2015; Bottani and Vignali, 2019; Sartoretti et al., 2019). Interconnection technology provides ways to establish warehouse information collection and exchange, which could be a leading factor for future warehouse development. IoT and CPS technologies, including Radio frequency, pick to light, and pick by voice, are commonly used in the warehouse picking process. The brief introduction on interconnection technology could bring some insights for a better understanding of the smart warehouse. To formulate a way of choosing suited interconnection technology, Hassan et al. (2015) identify the affecting factors of warehouse automatic identification technology through a literature review. The major affecting factors for selecting automatic identification technology include organizational, operational, structural, resources, external, environmental, and technological factors.

RFID is a technology for automatic object identification and data collection based on radio waves. Among the interconnection technologies, RFID is considered a choice for positioning, identifying, information interaction, and warehouse management in the smart warehouse. Its strengths include non-contact sensing ability, high flexibility, configurability, high efficiency, and low cost (Tao et al., 2014). Giusti et al. (2019) work on a generalized performance comparison model of different RFID implementations. The benefit related to informatization on warehouse performance has been investigated. A probabilistic risk assessment model is applied to identify and quantify the delay value in transfer time.

The application of RFID in smart warehouses mainly focuses on inventory tracking, localization, and warehouse management. Information exchange, which is the main function of the RFID system, significantly impacts the warehouses' efficient communication. Information accuracy is essential for managing warehouse information

Table 3 Summary of the reviewed literature

Category	Article	Level			Warehouse system	Decision problem	Topics	Method				
		Strategic	Tactical	Operational				TM	QN	MP	AL	SI
Movement characteristics	Yang et al. (2015b)	√			Compact AS/RS	Rack design	Acceleration and deceleration of S/R machine	√				
	Wang et al. (2015)	√		√	SBS/RS	Task scheduling	Movement characteristics of shuttles and lifts	√	√		GA	
	Lamballais et al. (2017)	√			RMFS	Performance evaluation	Realistic robot movement	√	√			
Command cycle	Xu et al. (2015)	√			AS/RS	Travel time models	Quadruple command cycle	√				
	Salah et al. (2017)	√			Wire-driven robots	Travel time models	DC for random and class-based storage	√				√
	Lerher (2018)	√			AVS/RS	Travel time models	DC	√				√
	Liu et al. (2018)	√			Split-platform AS/RS	Travel time models	DC with a dedicated lift per rack and a dedicated lift per job type	√				√
Battery management of robots and AGVs	Zou et al. (2018b)		√		RMFS	Battery recovery method evaluation	Battery charging and swapping	√	√			√
	Kabir and Suzuki (2018)		√		AGV	System flexibility and battery management	AGVs battery management					√
	Cheng et al. (2021)		√		Mobile robots	Scheduling of mobile chargers	Mobile chargers, robot charging strategy	√	√		HA	√
Handling speed	Zou et al. (2017)		√		RMFS	Assignment rule of workstations to robots	Handling speeds of workstations	√	√		NS	√
Storage assignment	Guo et al. (2016)	√	√		Forklift warehouse	Impact of storage space on storage policy	Storage policies	√			DP	
	Ramtin and Pazour (2015)	√	√		AS/RS	Product to pick position assignments	Demand curves of products	√			HA	√
	Pan et al. (2015)		√		Pick-and-pass systems	Storage space assignment	Workload balance of each picking zone				GA	√
	Manzini et al. (2015)		√		Storage systems	Storage capacity, storage assignment, and optional subsystems selection	Product life cycle			√		
	Yuan et al. (2019)		√		RMFS	Storage assignment	Velocity-based storage policy	√			HA	√
	Yu et al. (2015)	√	√		Warehousing system	Optimal number and boundaries of storage classes	Class-based storage	√			HA	√
	Zaerpour et al. (2017b)		√		Puzzle-based compact storage system	Configuration of two-class-based storage	Class-based storage			√	HA	
	Zaerpour et al. (2017c)		√		Puzzle-based CS	Two-class-based storage assignment	Class-based storage	√				

(*Continued*)

Category	Article	Level			Warehouse system	Decision problem	Topics	Method				
		Strategic	Tactical	Operational				TM	QN	MP	AL	SI
	Kress et al. (2017)		√		Storage systems	Stock Keeping Units partition problem	Dedicated storage			√	HA, BB	
	Zaerpour et al. (2015)		√		Compact AS/RS	Storage assignment for fast retrieval	Shared storage			√	HA	
	Zou et al. (2018a)		√		Robotic compact storage system	Evaluation of storage policies	Dedicated storage, shared storage	√	√			√
Order processing	Man et al. (2021)			√	AS/RS	S/R machine sequencing	Sequencing			√	ε, GA, HA	
	Wang et al. (2020c)			√	SBS/RS	Retrieval task sequencing	Sequencing			√	AC, TS, SA	
	Emde et al. (2020)			√	AS/RS	Single batching machine scheduling	Batching			√	BD	
	Foumani et al. (2018)			√	Robotic AS/RS	Sequence of orders, sequence of items	Sequencing			√	CE	
	Gagliardi et al. (2015)			√	AS/RS	Globally sequencing approaches	Sequencing				HA	√
	Nicolas et al. (2018)			√	Vertical lift modules	Order batching	Batching			√	SA, TS, GA	
	Lenoble et al. (2021)			√	Carousels	Fixed and rolling batching	Batching	√		√	HA	
	Xie et al. (2021)			√	RMFS	Assignment of pods and orders to picking stations	Splitting			√	HA	√
	Jiang et al. (2021)			√	AGV	Order batching and batch assignment	Splitting, batching			√	CG, HA	
	Boywitz et al. (2019)			√	A-frame system	Replenishment problem and picking order sequencing	Replenishment, sequencing			√	GR, LS	√
	Jiang et al. (2020)			√	RMFS	Picking-replenishment synchronization	Replenishment			√	VNS	√
Retrieval location assignment and scheduling	Yang et al. (2015a)			√	SBS/RS	Joint location and sequence assignment	Location and sequence			√	TS	
	Heshmati et al. (2019)			√	Crane-operated warehouse	Location assignment and multi-crane scheduling	Location and scheduling			√	HA	
	Yang et al. (2015c)			√	SBS/RS	Location and sequence assignment	Location and sequence			√	VNS	
	Boysen et al. (2017)			√	RMFS	Order batching and sequencing	Rack assignment and batching, sequencing			√	SA	
	Weidinger et al. (2018)		√	√	RMFS	Storage assignment and rack parking optimization	Storage assignment, rack assignment			√	ALNS	

(*Continued*)

Category	Article	Level			Warehouse system	Decision problem	Topics	Method				
		Strategic	Tactical	Operational				TM	QN	MP	AL	SI
	Gharehgozli and Zaerpour (2020)			√	RMFS	Robot scheduling with multiple locations of pods	Robot scheduling, rack assignment			√	ALNS	
Resource allocation and differentiated service	Gong et al. (2021)			√	RMFS	Order fulfillment	Differentiated customer classes	Markov model				
	He et al. (2018)		√	√	AGV	Storage assignment with differentiated probabilistic queueing strategy	Differentiated service policy	√	√		AM, SA	
	Wauters et al. (2016)			√	Miniload AS/RS	Location assignment and storage and retrieval scheduling	Prioritized waiting time			√	HA	
	Yuan and Gong (2017)		√	√	RMFS	Optimal number and the velocity of robots	Robots pooled strategy	√	√			√
	Roy et al. (2019)		√	√	RMFS	Comparison of dedicated and pooled zone assignment strategy	Robots pooled strategy	√	√			√
Blocking rearrangement	Lerher (2016)	√		√	SBS/RS	Travel time model	Rearrangement of blocking totes	√				
	Xu et al. (2016)	√		√	AS/RS	Travel time model, optimal fill-grade factor decision	Rearrangement of blocking totes	√				√
	Chen et al. (2015)	√		√	Flow-rack AS/RS	Travel time model	Restorage of blocking unit-loads	√				√
	Boywitz and Boysen (2018)		√	√	CS	Robust storage assignments	Block prevention by storage assignment			√	LA	√
	Chen et al. (2016)		√	√	Flow-rack AS/RS	Retrieval sequencing	Block prevention by storage assignment			√	HA	
Conflict-free routing	Roy et al. (2015b)	√		√	AVS/RS	Congestion effects evaluation	Estimation of congestion delay		√			√
	Zhang et al. (2018)			√	AGV	Collision-free routing	Collision classifications and solutions				PA	
	Lee et al. (2020)			√	AGV	AGV scheduling in narrow aisle warehouses	Aisle access policies			√	NS	
	Han and Yu (2020)			√	Robot	Diversified-path database-driven multi-robot path planning	Collision free path planning				PA	
	Małopolski (2018)			√	AGV	Conflict-free operation	Collision and deadlock prevention				PA	√
	Thanos et al. (2019)		√	√	Vehicles	Dispatch and conflict-free routing with storage allocation	Conflict-free routing				HA	
	Zhao et al. (2020b)			√	AGV	Dynamic resource reservation-based method for collision avoidance	Collision avoidance				HA	
	Saidi-Mehrabad et al. (2015)			√	AGV	Job shop scheduling and conflict-free routing	Conflict-free routing			√	AC	

(*Continued*)

Category	Article	Level			Warehouse system	Decision problem	Topics	Method				
		Strategic	Tactical	Operational				TM	QN	MP	AL	SI
	Digani et al. (2015)			√	AGV	Coordinating a fleet of AGVs	AGV coordination				HA	
	Draganjac et al. (2016)			√	AGV	Decentralized control of AGV fleets	AGV coordination				HA	
	Digani et al. (2019)			√	AGV	Centralized AGV control strategy	AGV coordination			√	HA	√
	Yoshitake et al. (2019)			√	RMFS	Real-time holonic scheduling	Holonic scheduling				HA	√
Sustainable warehouse strategic and tactical decision	Meneghetti and Monti (2015)	√			Refrigerated AS/RS	Rack configuration, surfaces, and volumes of the cold cell	Energy consumption			√		
	Tappia et al. (2015)	√			AVS/RS, AS/RS	Comparison of automated warehousing system	Energy consumption	√				
	Gružauskas et al. (2018)	√			Autonomous vehicles	Energy and economic impact of autonomous vehicles	Energy consumption					√
	Yetkin Ekren et al. (2018)	√			SBS/RS	Time, variance, and energy-related performance estimations	Energy consumption and regeneration	√				√
	Yetkin Ekren (2021)	√			AVS/RS	Optimization of system design	Energy consumption and regeneration	√				√
	Zaerpour et al. (2017a)	√			Puzzle-based CS	System evaluation and optimization	Energy consumption	√				√
	Li et al. (2020)		√		RMFS	Storage assignment	Energy consumption	√				√
	Roozbeh Nia et al. (2017)			√	AS/RS	Dynamic sequencing of storage and retrieval	Carbon emission	√			GA	
	Ene et al. (2016)			√	Picker-to-part warehouse	Batching and picking optimization	Energy consumption				GA	
	Habibi Tostani et al. (2020)			√	AS/RS	Crane scheduling	Energy consumption			√	CC	
	Hahn-Woernle and Gunthner (2018)			√	AS/RS	Power-load management and its impact	Power-load management					√
	Basso et al. (2019)			√	Electric vehicles	Vehicle scheduling	Battery charging, electricity price			√	GR	

Notes: TM: travel time/distance model; QN: queuing network model; MP: mathematical programming; AL: algorithm; SI: simulation; CS: compact storage system; S/R: storage/retrieval; ε: ε-constraint method; GA: genetic algorithm; NS: neighborhood search algorithm; VNS: variable neighborhood search algorithm; DP: dynamic programming algorithm; BB: branch and bound algorithm; AC: ant colony algorithm; TS: tabu search algorithm; SA: simulated annealing algorithm; BD: Benders decomposition algorithm; CE: cross-entropy method; HA: heuristic algorithm; GR: greedy algorithm; ALNS: adaptive large neighborhood search; AM: alternating minimization algorithm; PA: path-planning algorithm; LA: left-edge algorithm; CC: cooperative coevolutionary algorithm; CG: column generation algorithm; LS: local search procedure.

exchange efficiency and effectiveness (Zhong et al., 2015).

Object localization based on RFID technology serves as a major function of RFID warehouse management. One of the most challenging issues in RFID-based applications is the acquisition of location information of either the tags or readers. Thus, RFID-based localization (especially three-dimensional localization) has been an active research topic (Lu et al., 2018). The use of tracking inventory is also investigated by researchers (Shahzad and Liu, 2015; Zhou et al., 2017; Mo and Li, 2019; Gareis et al., 2021). Missing tags searching is another RFID object location and inventory tracking application (Chen et al., 2017).

IoT and CBS technologies can also influence the way of warehouse design and operation. RFID tags are attached to products at the item level instead of the pallet level, providing a way to support warehouse storage assignment with higher precision (Choy et al., 2017). RFID can provide infrastructure for collaborative warehouse order fulfillment of decentralized management to improve system reaction capabilities (Reaidy et al., 2015). The real-time information exchange and collection of RFID can provide a decision support tool for order fulfillment (Lam et al., 2015). Furthermore, the energy-saving improvement of RFID could be a new point for the warehouse system.

In some research about conflict-free routing in the robotized warehouse, CPS is used for information exchange and pre-detection of potential collisions. Collisions can be detected by comparing the occupancy of the time window, and some corresponding collision avoidance strategies can be developed for conflict-free routing (Lee et al., 2019; Keung et al., 2020).

WMS is a computerized database application widely used by the logistics section for warehouse control and optimization. A common WMS includes warehouse processes including receiving, storage, order picking, packing, and shipping. IoT provides ways for information collection and exchange for WMS. The implementation of IoT-based WMS can also facilitate warehouse operation. Qiu et al. (2015) introduce a framework of IoT-enabled Supply Hub in Industrial Park (SHIP). The innovations of IoT-enabled SHIP include different information sharing levels, information structure, and decision-making tools. Lee et al. (2018) propose an IoT-based WMS integrated with the fuzzy logic technique. Based on the case data, the IoT-based WMS shows its competitiveness in improving warehouse productivity, picking accuracy, efficiency, and robustness in order variability.

4 Equipment automation

Warehousing is often seen as a labor-intensive activity. Managing the traditional manual warehouse has become a critical problem for performance improvement with great complexity (Yu and de Koster, 2009). This problem is dealt with by equipping many warehouses with automation equipment. Automation is the technology used to process tasks with minimal manual labor. It changes warehouse operation in many aspects, including increased efficiency, agile reaction to customer orders, and a significant reduction in labor costs and errors. Automated parts-to-picker order picking systems have become popular for warehouse operations (Tappia et al., 2019). The increase in the application of automation facilities is significant; consequently, finding optimal strategies for the design and control of automated warehouse systems becomes more challenging with the growth and penetration of modern computer technology (Amato et al., 2005).

When applying automation technology to warehouse design and operation, exploring the internal relationship of strategic and tactical decisions along with some system characteristics is important. This section will go through various automated equipment used in smart warehouse and figure out some system characteristics that can be used as important factors of strategic and tactical decisions in smart warehouses.

AS/RS is a widely equipped warehousing system in warehouses and distribution centers for automatic material handling with high speed and accuracy (see Fig. 7). It is the combination of automatic equipment and corresponding control policies (Lee and Schaefer, 1996). Although AS/RS has been widely adopted for years, the research on its operational decision is still of great value, which can provide basic references for various warehouse technologies in smart warehouses. Today, AS/RS has evolved into an efficient system with many variants, including AVS/RS (Lerher et al., 2021), SBS/RS (Zhao et al., 2020a; Yetkin Ekren and Akpunar, 2021), compact AS/RS (Hao et al., 2015; Xu et al., 2018; Kumawat and Roy, 2021), and puzzle-based storage and retrieval system (Mirzaei et al., 2017; Yalcin et al., 2019). The system configuration of AS/RS and its variants can be affected by many factors, such as the configuration of rack (Yetkin Ekren, 2017), aisle (Roy et al., 2015a; Manzini et al., 2016), cross-aisle (Tutam and White, 2019a), space (Derhami et al., 2019), tier (Tappia et al., 2017), shape (Tappia et al., 2017; Tutam and White, 2019b), depot (Gharehgozli et al., 2017; Gharehgozli et al., 2021), shuttles (Ha and Chae, 2019), and pick position (Liu et al., 2021). Some tactical policies

Fig. 7 A typical AS/RS (accessed via daifuku-logisticssolutions.com/en/product/asrs/index.html).

can also take effect on the system design and performance, such as storage policy (Ang and Lim, 2019), dwell point policy (Yu and Yu, 2019), and input/output point policy (Xu et al., 2020). Travel time is a key indicator to evaluate the system efficiency, which is measured by the maximum of the isolated horizontal and vertical travel times (Chen et al., 2020) and is thus applied in warehouse strategic and tactical design (Epp et al., 2017).

AGV is a driverless material handling equipment for horizontal material movement (see Fig. 8). AGV-assisted order picking can adapt to order picking of small-sized items and heavy items. Based on AGV technology, AMR and robotized warehouse systems are developed to assist or replace human labor in product picking and handling. AGV-based warehouse systems and robotized warehouse systems are increasingly applied in warehouses.

Fig. 8 AGV-assisted order picking (accessed via directindustry.com/prod/crown/product-9227-1769803.html).

RMFS, or so-called KIVA system, is an automated, parts-to-picker picking system in which a fleet of robots can move racks (inventory pods) with products toward picking workstations (Wang et al., 2020b). It shows greater flexibility and productivity through its flexible layout and hardware installation (Bozer and Aldarondo, 2018). The key decisions in the RMFS design include the number of robots, the shape of the forward area, the number of pods per stock keeping unit (SKU), the ratio of the number of picking stations and replenishment stations, and the replenishment level (Aldarondo and Bozer, 2020; Lamballais Tessensohn et al., 2020). The travel time and operation cycle of robots in RMFS are investigated by Wang et al. (2020a). Other types of robots for parts-to-picker picking modes, such as cable-driven parallel robots (Zhang et al., 2020), rack-climbing robots (Azadeh et al., 2019b), and robot with transport and lifting capabilities (Zou et al., 2018a), are also powerful equipment in smart warehouses.

Warehouse robots in the picker-to-parts mode can perform collaborative picking with human pickers to minimize the pickers' travel times and distances (Ghelichi and Kilaru, 2021). Two types of warehouse robots are mentioned in Lee and Murray (2019)'s research. One type of warehouse robots can grasp items from the shelf, and another type of robots can deliver items from the picker to the workstation. Robots can also perform sorting of the picked items (Fager et al., 2021).

4.1 Strategic decision

With respect to the travel time in strategic warehouse design, the system characteristics cannot be neglected since they will directly influence the system's overall performance. The specific characteristics can be different in different warehouse systems. In this part, we will go through the effect of system characteristics, including movement characteristics, command cycle, battery charging for RMFS and AGV systems, and the efficiency of the picking station.

In AS/RS, the movement characteristics are usually referred to as acceleration/deceleration and the speed of the storage/retrieval (S/R) machine, which can directly influence the actual travel time, especially in the circumstance of frequent start and stop. Based on the consideration of acceleration/deceleration, the speed profile is an important influence factor of optimal storage rack design (Yang et al., 2015b). The acceleration/deceleration of shuttles and lifts significantly impacts task scheduling (Wang et al., 2015). The robot driving behavior can influence RMFS design. Lamballais Tessensohn et al. (2017) work out an evaluation model addressing warehouse layout aspects of RMFS considering robots driving behavior. The location of the workstations can influence maximum order throughput, while changing the length-to-width ratio of storage area has limited influence on order throughput.

Command cycle is a concept that defines the operation pattern of warehouse systems. Two types of command cycle are commonly used: Single command cycle (SC) and dual command cycle (DC) (Pan and Wang, 1996). In DC operation mode, storage and retrieval operations are combined within a movement. DC will result in better performance in most cases. Other operation modes, such as the quadruple command cycle (Xu et al., 2015), have also been analyzed in previous research. Some works have evaluated the influence of command cycles on system configurations (Salah et al., 2017; Lerher, 2018). For some special variants of AS/RS, the command cycles could have different meanings. Split-platform automated storage and retrieval systems (SP-AS/RSs) are used for handling overly heavy loads like containers. Liu et al. (2018) study two DC expected travel time models for SP-AS/RS: An SP-AS/RS model with a dedicated lift per rack and another model with a dedicated lift per job type.

In RMFS and AGV-assist picking system, robots and AGVs are battery-powered. The battery life is limited to certain working hours, which depends on battery capacity and working intensity. Once the battery exhausts, it needs to be charged or swapped. According to the research finding of Zou et al. (2018b), the common battery management strategies include battery swapping, battery charging strategy with a plug-in, and inductive charging of the battery. Among the three strategies, inductive charging is the best strategy based on system throughput time. From the cost perspective, battery swapping costs more than other strategies. Another research point for battery management is the duration of battery charging. More AGVs' productive hours can be achieved by reducing the duration of each charge and increasing the frequency of recharging (i.e., recharging the batteries to below 100 percent of full capacity). This strategy provides a way to realizing the productivity and flexibility of the AGV system (Kabir and Suzuki, 2018). Mobile chargers can be used to charge the battery-powered machines on duty locations. The adoption of mobile chargers improves the flexibility of the charging process. Cheng et al. (2021) study the minimum required quantity of mobile chargers and the scheduling of mobile chargers for power supplements of robots.

Handling speeds of workstations may influence the design and operation of warehouses. Zou et al. (2017) design a model with neighborhood search algorithm to obtain a better robot assignment for online retailers. Semi-open queueing network models and an approximate two-phase approach are presented to evaluate the proposed assignment rules. Furthermore, the appropriate size of shelf blocks is designed based on the examined assignment rules.

4.2 Tactical decision

Storage assignment allocates the storage locations to items. It can be a conductive factor to warehouse strategic and operational decisions. Different storage policies can influence the optimal warehouse shape and storage space (Guo et al., 2016). For example, the operational decision, picking position assignment, and workload balance among pickers can also be influenced by the storage policy (Pan et al., 2015; Ramtin and Pazour, 2015).

Class-based storage policy is one of the most commonly used storage policies in practice. It divides stored items into different classes according to product characteristics such as demand, product turnover, and life-cycle (Manzini et al., 2015; Yuan et al., 2019). A small number of storage classes in a class-based storage policy is usually optimal (Yu et al., 2015). Under class-based storage policy, different system configurations and first zone boundary can result in different system performances (Zaerpour et al., 2017b; Zaerpour et al., 2017c).

All SKUs of the same type are stored in a unique storage position in a dedicated storage policy. Kress et al. (2017) formalize a storage partition problem that subdivides items into disjoint subsets aiming to minimize the number of groups accessed in retrieving process and show its applicability in storage systems with a dedicated storage policy.

A shared storage policy allows multiple products to share one storage rack. Retrieval time and storage utilization can be improved through shared storage (Zaerpour et al., 2015). According to Zou et al. (2018a)'s study, in robotic compact storage and retrieval systems, dedicated storage policy performs better than shared policy in terms of throughput time. In contrast, the shared storage policy is more sustainable from a cost perspective.

5 Process integration

The operations management of the various processes in warehouses is logically interrelated. In a well-managed warehouse, the consideration of interactions among various processes should be put forward for further improvement of warehouse performance. Thus, integrated planning in warehouse operations management should be implemented. van Gils et al. (2018a) reveal the interactions and relations among storage, batching, zoning, and routing policies of the order picking process. The results indicate that the integrated decision of different processes can attain remarkable benefits in warehouse research and operations. van Gils et al. (2018b) further review the combinations of order picking planning problems in warehouse system design. The two reviews highlight the research value of combinational problems in warehouse operations management. This section will go through the research of smart warehouses at the operational level and determine some topics related to the integrated decision-making of smart warehouse operations management. The first two topics are order processing and location assignment, which try to implement overall planning in smart warehouse operation. The other two topics are resource allocation and differentiated service and blocking rearrangement and conflict-free routing, which deal with the new problems raised in smart warehouse operation.

5.1 Order processing

Orders released to the system usually contain the demand information and attributes, such as task release time and due date (Man et al., 2021). Orders may be sequenced, split, or batched to consolidate the scattered demand and reduce the unproductive works of order pickers (Emde et al., 2020; Wang et al., 2020c).

Order sequencing mainly determines the sequence of orders to be processed. Proper sequencing can reduce the unproductive movement of the equipment and thus reduce the total travel time and makespan (Gagliardi et al., 2015). Foumani et al. (2018) adapt the traveling salesman problem to a robotic AS/RS with a cross-entropy method to find the optimal sequence of orders and optimal sequence of multi-location items inside each order.

Order batching is a way to eliminate the inefficiency of piece picking, in which the scattered demands from different orders are consolidated and fulfilled as a batch. A batch is composed of a subset of orders and the set of items corresponding to these orders. The productivity of order batching on system throughput is significant in automated warehouses (Nicolas et al., 2018). The order batching method applied in research is usually fixed batching, where all orders belonging to a batch are collected before the next batch is started. According to Lenoble et al. (2021), rolling batching, where a new order immediately replaces each completed order belonging to the current batch, and other dynamic batching methods can improve system efficiency in terms of throughput time.

As the contrast of order batching, the split order means that an order is divided into two or more parts for picking, and different pickers may pick these parts. The power of order splitting in RMFS and the assignment of pods and orders to picking stations are investigated by Xie et al. (2021). Jiang et al. (2021) investigate the integrated decision of order splitting, batching, and batch assignment by constructing a two-stage optimization model. The first stage of the optimization model works out order splitting and batching strategy, and the second stage assigns the batches formed in the first stage to AGVs for order fulfillment.

Most of the warehouse picking literature concerns the optimization of the picking process, while considering the picking and replenishment process remains an open topic. A proper order sequencing can facilitate the replenishment process and prevent stock-outs in A-frame system with fewer workers (Boywitz et al., 2019). In RMFS, the decision problem of order picking and batching along with the replenishments could reduce the total shelf visits (Jiang et al., 2020).

5.2 Retrieval location assignment and scheduling

Warehouse systems need to perform retrieval tasks so that the items stored in warehouses can be accessed. The retrieval tasks raise two interrelated decisions, namely, location assignment and retrieval scheduling. Location assignment is about how to determine the selection of the locations for the retrieval items. Retrieval scheduling establishes the schedule of warehouse equipment for the retrieval process. The two decisions often interact with each other in real-life examples. The trade-off of the two decisions must be carefully considered to optimize the total travel time (Yang et al., 2015a; Heshmati et al., 2019). Besides, proper storage policies, such as shared storage policy, can benefit location assignment and retrieval scheduling (Yang et al., 2015c).

In RMFS, the retrieval location assignment problem can be interpreted as selecting racks for the retrieval items. The objective can be either minimizing travel time or minimizing the number of rack visits. Order sequencing and batching can affect the decision of location assignment. Boysen et al. (2017) carry out a typical integrated order processing problem, where order sequencing, rack visits, and the study of the shared storage policy are optimized. Weidinger et al. (2018) propose the problem of rack parking location assignment during order processing in RMFS. An interval scheduling problem is formalized for the problem, and a metaheuristic dubbed adaptive programming is introduced to solve the problem.

5.3 Resource allocation and differentiated service

Robots are critical resources in RMFS. Some resource allocation strategies are imposed on robots to enhance system utilization. Resource pooling strategy refers to group available resources together to maximize utilization of resources and counteract variability in the division of resource management. The dedicated strategy in RMFS refers to that a robot appears as a dedicated resource in the system. In contrast, the pooled strategy breaks the property of dedicated resources to allow a robot to process needed tasks. In Yuan and Gong (2017)'s research, two protocols in sharing robots among order pickers are investigated. The advantage of the pooled strategy is presented by reducing the optimal number of robots needed and the throughput time. Roy et al. (2019) compare the efficiency of dedicated and pooled strategies for zone control in RMFS with single and multiple storage zones. The pooled strategy outperforms the dedicated strategy in terms of the expected throughput time of the picking process. However, the replenishment process under the pooled strategy may take a longer time.

E-commerce companies are moving toward customer differentiation and prioritization. The differentiation and prioritization in warehouse operations indicate the different classes assigned to orders. The class is usually based on price or customer priority, and orders with higher classes are attached with tighter time limits than the lower-class orders. Warehouses should prioritize the allocation of resources to ensure the fulfillment of higher-class orders. Under this setting, the common objectives for prioritized order picking are to minimize total travel time or distance. In Gharehgozli and Zaerpour (2020)'s research, different priorities are attached to orders based on the order urgency. The research setting of Gong et al. (2021) states that the expedited shipping requests will be immediately processed when a robot is available. Weights can be used to characterize prioritization. In He et al. (2018)'s research, some AGVs are dedicated to certain classes of orders. The weighted latency for different price-based classes of customer orders is optimized. Wauters et al. (2016)'s research minimizes prioritized waiting time of storage and retrieval scheduling problem. The prioritized waiting time is calculated by the weighted sum of waiting time, in which the weights are determined by customer priority.

5.4 Blocking rearrangement and conflict-free routing

Warehouse operators usually encounter some unproductive activities, such as rearranging blocking items and route congestion. These unproductive works are not value-added and can lead to system inefficiency. Some special strategies should be implemented to avoid unnecessary works.

The blocking problem usually occurs in a unit-load warehouse or palletized warehouse. The blocking unit-loads may block the requested unit-loads if the storage position or sequence of the unit-loads is misallocated. The blocking unit-loads need to be rearranged and repositioned to a free storage location to retrieve the requested unit-loads. The selection of the free storage locations for blocking rearrangement usually follows the rule of rearrangement of the nearest location, which will reposition the unit-loads to the nearest free storage location (Lerher, 2016). Other rearrangement rules include rearranging to a random location and rearranging to a deterministic point. The rearrangement to the nearest location rule performs the best in terms of expected rearrangement time (Xu et al., 2016). In a flow-rack AS/RS, unit-loads are stored on the flow racks' storage face, and slided down to the retrieval face where the retrieving process is processed. The blocking problem in a flow-rack AS/RS may be more troublesome because only the unit-loads on the retrieval face can be directly retrieved. To evaluate the blocking effect in flow-rack AS/RS, Chen et al. (2015) propose a travel time model of bi-directional flow-rack AS/RS where adjacent columns of racks slope to the opposite directions to rearrange blocking unit-loads within the same face directly.

Proper storage assignment and retrieving scheduling can eliminate the possible rearrangement of blocking unit-loads. Boywitz and Boysen (2018) propose a robust storage assignment to protect against the uncertainty of due dates to avoid blockings and excessive retrieval effort. Chen et al. (2016) investigate the sequencing of storage and retrieval operation in flow-rack AS/RS with duration-of-stay storage policy to minimize the total travel time and eliminate restoring of blocking unit-loads.

A route in the AGV-assist picking system implies the path that AGV should follow. When performing storage and retrieval operations, the routes of two or more AGVs may conflict, resulting in blocking or colliding. The blocking and collision problem of AGVs may appear within aisles, along the cross aisles, or at the intersections of aisles and cross-aisles. Route intersection must be concerned to avoid collision and unnecessary waiting (Roy et al., 2015b).

According to Zhang et al. (2018), the warehouse collision can be classified into four types: Head-on collision, cross collision, node-occupancy collision, and shelf-occupancy collision. The head-on collision happens if two AGVs move in the opposite direction on the same path at the same time or pass the same workstation at the same time. The cross collision happens when two AGVs compete for the workstations at the intersections. The node-occupancy collision happens when an AGV stops at a point on another AGV's incoming route. The shelf-occupancy collision happens when a shelf (rack) stops at a point on another AGV's incoming route. Based on these classifications, three solution strategies are carried out: Selecting the candidate route, waiting for a short period before starting, and modifying the routes. These classifications and solutions provide a framework for conflict-free routing.

Zone control is a simple way to avoid collisions, where a zone (usually an aisle or a zone that contains several aisles) is occupied by only one AGV. In Lee et al. (2020)'s work, two aisle access policies are proposed to prevent head-on collision and blocking of AGVs. The exclusive policy indicates that an AGV must not access an aisle if another AGV is already inside. The parallel policy indicates that AGVs can enter the same aisle simultaneously if they do not cross.

The warehouse layout can be simplified as a grid model or abstracted by square topology method in which the ground of the warehouse is divided into many squares. The squares can represent different properties in warehouses, such as aisle and pick-up position, and the driving routes can be expressed as several consecutive squares. Square topology method provides a simplified method to detect the potential route intersection and collision of robots (Han and Yu, 2020). Based on this, Małopolski (2018) proposes a method for collisions and deadlock prevention based on chains of elementary reservations. The warehouse layout can be further abstracted as nodes and arcs in the undirected graph (Thanos et al., 2019). Zhao et al. (2020b) use dynamic resource reservation for scheduling and collision avoidance of AGV warehouse with graph model. Saidi-Mehrabad et al. (2015) propose an integrated model of conflict-free routing and job shop scheduling.

System coordination requires considering the whole system to improve the global performance instead of focusing only on a single aspect of the system. Coordination of AGVs and robot fleets is a solution for improving production efficiency and flexibility and eliminating congestion and collision in warehouse systems (Digani et al., 2015). The system's control can be decentralized (Draganjac et al., 2016) or centralized (Digani et al., 2019). Decentralized approaches directly address the complexity of large-scale multi-robot coordination problems, whereas centralized approaches can find the optimal global solutions. Furthermore, holonic scheduling method can be applied to coordination scheduling (Yoshitake et al., 2019).

6 Environmental sustainability

Climate change, resource shortage, and other environmental problems have posed significant threats to the future of human society. The term “sustainability”, which progressively incorporates social, environmental, and economic responsibilities, is primarily about the development process that meets the present needs without compromising the ability of the future. In the logistics section, sustainable logistics and supply chain management is carried out to seek improvements in their environmental performance and gain the competitive edge in an eco-friendly way (Dadhich et al., 2015; Yu et al., 2016; Shi et al., 2019).

Smart warehouses usually consume much more energy than traditional manual warehouses because more automated facilities are used in smart warehouses. Increasing energy consumption in warehouses becomes a major component of warehouse operational costs. Meanwhile, the increase in energy consumption produces extra carbon emissions to nature, which is the main cause of climate change. Sustainable warehouses aim to pursue sustainability goals, such as energy efficiency, greenhouse gas emission reduction, cost reduction, and throughput time minimization. Sustainability is a common thread running through strategic, tactical, and operational decisions of the sustainable warehouse.

In this section, we will summarize and reveal how the smart warehouse can achieve sustainability goals in warehouse operations management. Similar to the division of previous sections, the literature related to sustainable topics in smart warehouses is reviewed and categorized into two aspects: Strategic and tactical decision and operational decision.

6.1 Sustainable warehouse strategic and tactical decision

Different research topics and methods are attached to the sustainable warehouse’s strategic and tactical decision and evaluation. Energy consumption and carbon emission are major influence factors in sustainable warehouse design. Cold-chain logistics are essential to food supply chains to keep the freshness of products. Refrigerated AS/RS becomes a preferred choice for storage in cold-chain logistics since automated equipment is more adaptable in the cold environment than labors. In such a system, the refrigerator accounts for a large proportion of energy consumption. Reducing refrigeration energy consumption becomes a key problem in the sustainable design of refrigerated AS/RS. Meneghetti and Monti (2015) propose a sustainable design model for refrigerated AS/RS. The configuration of racks and cold cells are conjointly optimized to minimize the total yearly cost other than investments of the automated storage facility. The cost of energy consumption and greenhouse gas emissions for refrigeration and picking operations are considered in the model.

Compared with the traditional crane-based system, AGVs and shuttles in warehouses can achieve higher flexibility and efficiency in throughput and better environmental impact. In Tappia et al. (2015), energy consumption and environmental impact are selected as the indicators for comparing AS/RS and AVS/RS. The results point out that AVS/RS can achieve a win–win situation in economic and environmental performance. The sustainability feature of AVS/RS and SBS/RS in energy saving and carbon emission reduction is also demonstrated by Gružauskas et al. (2018) and Yetkin Ekren et al. (2018).

Energy regeneration could be another factor that affects sustainable strategic design. Yetkin Ekren (2021) presents a multi-objective solution approach considering the tradeoff between average cycle time and energy consumption. Energy consumption and energy regeneration by deceleration of vehicles and lifts are considered in the system. The result reveals that the cycle time is mainly influenced by the footprint shape, including the number of aisles, bays, and tiers. The energy consumption is mainly affected by the number of tiers. The Pareto optimal solutions of system design can be obtained by considering both performance measures simultaneously.

The concept of energy-efficient design can extend to other types of facilities. For example, Zaerpour et al. (2017a) derive a closed-form expected retrieval time formula of the live-cube system. The comparison between the live-cube systems and traditional systems is proposed to show the special feature of live-cube systems in investment, operational costs, and energy consumption.

For the tactical decision of the sustainable warehouse, a proper storage assignment can improve picking efficiency and reduce energy consumption. Li et al. (2020) propose a turnover rate-based decentralized storage policy of the KIVA warehouse and then carry out an energy-consumption-aware evaluation method for the storage assignment.

6.2 Sustainable warehouse operational decision

According to the literature reviewed, the sustainable goal can be realized in warehouse operational decisions by various methods, such as sequencing, scheduling, and power load management. To some extent, the win–win of environmental and operational objectives can be achieved in the sustainable warehouse because eliminating useless work can improve efficiency while reducing energy consumption.

Sequencing and scheduling optimization can take effect in energy saving and greenhouse gas reduction. Roozbeh Nia et al. (2017) investigate the improvement of greenhouse gas efficiency in unit-load multiple-rack AS/RS by a DC “dynamic sequencing” method. Habibi Tostani et al. (2020) propose a two-level optimization framework of dual shuttle cranes scheduling problems. The upper level optimizes class-based storage location assignment and inventory consideration to minimize the total cost and energy consumption. The lower level optimizes the multi-period scheduling of cranes in AS/RS, which involves the necessities of reward scheduling and workload balance to time windows. Ene et al. (2016) investigate the picking operation in warehouses to reduce energy consumption and find proper storage policy.

Sequencing and scheduling in the sustainable warehouse can be extended to the viewpoint of power-load management. Electricity suppliers usually charge higher prices at peak periods and lower prices at valley periods to users. Power-load management is a customer-side system used to avoid electricity peaks while making better use of electricity valleys. Power-load management sets thresholds to determine whether electric consumption in peak periods needs to be avoided. If the thresholds are jeopardized, some tasks will be delayed, and the machines stop to reduce power usage. Hahn-Woernle and Gunthner (2018) investigate the multi-aisle mini-load AS/RS operation problem from the power-load management perspective. The simulation result shows that electricity peaks can be avoided with only a small loss of throughput. In the AGV picking system, power-load management can be implemented by carefully scheduling the battery charging process to avoid higher electricity prices in peak time. Basso et al. (2019) expand the AGV battery charging problem to the electricity tariff varying by hour and exploit the availability of cheaper renewable energy sources. The study determines the charging schedule, including the start time of charging and the assignment of batteries to chargers.

7 Conclusions and future research

Smart warehouses play an important role in the future development of warehouses. In this review, we attempt an extensive review of the published research related to smart warehouses. From the contents above, the research on smart warehouses has attracted the attention of scholars, logistics, and other industries. The conclusions, future research opportunities, and limitations are listed below.

Information interconnection: Interconnection is a relatively new issue in warehouse operation, which IoT and CPS bring up. IoT, CPS, and other emerging interconnection technologies enhance information interaction within the warehouse system and the entire logistics chain. From the reviewed literature, we can find that RFID is the primary IoT technology used in warehouse operations. The application of other emerging technology, such as sensors and smart things in warehouse operation, needs to be studied. IT-enabled warehouse systems could be another research direction on the system configuration level. Besides, little research on warehouse operations management has been worked out considering the influence of interconnection technologies. The research on the interconnection issues of warehouse design and control has a broad foreground, for example, real-time control and dynamic decision-making of warehouse systems.

Equipment automation: Several automated warehousing systems are reviewed. The deployment of these systems requires large investments and careful planning at strategic and tactical levels. In the future, systems with higher automation levels, such as various warehouse robots, will be implemented broadly and will profoundly change the operation mode. Based on the status of the warehousing industry, research on the upgrade of existing warehouse systems may need more attention. For example, picking-assist facilities could be more popular, especially in system upgrades of traditional warehouses. Picking-assist facilities such as AMRs and robots can support the picking process of picker-to-parts warehouse and make better use of existing warehouse configuration. Other types of warehouse robots, like climbing robots, may change warehouse strategic and tactical decisions deeply. The research on the evaluation and system design of the emerging system could provide essential guidance for the system deployment.

Process integration: We attempt to review the operation and optimization in warehouse research by several common integration topics on the operational level, which is a relatively new review structure to our best knowledge. These topics cover major research fields of operations management and optimization. Meaningful expansion of these issues, such as integrating receiving and delivery with other warehouse operation processes, needs more attention. The integrated operation of the emerging warehouse system could be another direction that needs to be addressed. Most existing research still focuses on the operations of the traditional systems, such as crane-based systems. To ensure the completeness of this part, we select some literature that focuses on these traditional systems. We think the operations of these systems may provide some reference and inspiration to the emerging systems. For example, the operation of the block-stacking system may provide some insights into the operations management of the robotic compact storage system mentioned in Zou et al. (2018a)'s study because of the similarities of the two systems. The content of process integration still needs to be expanded by the future research of the emerging systems.

Environmental sustainability: According to our review, appropriate strategic, tactical, and operational strategies are carried out to achieve the sustainable development objective in the warehouse section. Energy saving is the mainstream in sustainable warehouse development. More energy-saving methods and technologies, such as energy regeneration, the use of green energy sources, and power-load management, need to be studied and promoted. The focus of green warehousing may extend to some related activities and concepts, such as the overall energy consumption of all related activities, environmental certifications, and policies. Other sustainability topics, such as the design and operation of the reverse logistics warehouse, are still waiting to be solved. Furthermore, social and human factors can be another target for warehouse sustainability. Some scholars have investigated the human factors in the order picking process of the traditional warehouse (Grosse et al., 2017; Glock et al., 2019). The adoption and operation of smart warehouses remain potential opportunities and barriers from the human-centric perspective. The impact of management skills, mindsets, and other human factors could influence the performance of technology adoption (Mahroof, 2019). The impact of human factors on the operations management of smart warehouses can be further discussed in future research.

Warehousing is a fundamental component in logistics and supply chain management. To date, the research focusing on smart warehouses is still small in numbers of the overall warehousing research. Many challenging research problems are still waiting to be discovered and solved. Further effort should be made in smart warehouse operation research and the development of smart warehouse practice.

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